OPEN-LOOP DIVERSITY TECHNIQUE FOR SYSTEMS EMPLOYING FOUR TRANSMITTER ANTENNAS

Technical Field

This invention relates to the art of wireless communications, and more
5   particularly, to wireless communication systems using multiple antennas at the
transmitter and one or more antennas at the receiver.

Background of the Invention

It is known in the art that systems using multiple antennas at the transmitter and
one or more antennas at the receiver can achieve dramatically improved capacity, i.e., the
10   maximum bits/second/hertz with error free communication, as compared to single
transmitter antenna systems. It is also known in the art that if a channel estimate, or
channel statistics based on the channel estimate, are fed back to the transmitter, then the
throughput of the channel can be improved with respect to an identically configured
system but without feedback. However, because in systems with multiple transmit
15   antennas the overall channel is actually made up of multiple channels, with one channel
for each transmit and receive antenna pairing, such feedback requires considerable
bandwidth, and it is undesirable to dedicate so much bandwidth to feedback. Also, for
fast changing wireless channels, the feedback may not arrive at a fast enough rate in order
to be useful.

20   In order to achieve the maximum open loop capacity of a multiple transmit
antenna system, it is necessary to employ channel coding. The state of the art of channel
coding, e.g., turbo codes, trellis codes and the like, is typically spatially one dimensional,
i.e., they are designed for only a single transmit antenna. Generally, it is not immediately
obvious how one could employ such coding in a spatially multi-dimensional, e.g.,
25   multiple transmit antenna, system. In the case of two transmit antennas and one receive
antenna, it was recognized that each of the data substreams could be independently coded
using known channel coding techniques to achieve maximum capacity if so-called
"space-time spreading" was used. See for example, United States Patent Application
Serial No. 09/285578 entitled Space-Time Spreading Method Of CDMA Wireless
30   Communication.

Summary of the Invention

We have recognized that it is possible to employ conventional channel coding when using four transmit antennas, by using a decoupled space-time coding approach for each of a number, L, of data substreams that are derived from the overall source bit

5   stream. To this end symbols, which are samples of the data substreams after encoding, if any, are processed so that the resulting derivatives thereof, which includes at least the complex conjugate of one of the symbols, are grouped to form four transmit time sequences each spanning L symbol periods. The four time sequences may be viewed as forming a transmission matrix **B**. Each row of the matrix corresponds to a transmit

10   element, e.g., an antenna, and the elements of each row represent the samples of a temporal sequence that is emitted by the antenna in L symbol periods. In one embodiment of the invention, the number of data substreams L is equal to four, the number of antennas. The overall symbol rate for each antenna is the same as the symbol rate of the original overall source bit stream. In accordance with the principles of the

15   invention, the matrix **B** is arranged as follows:

$$\begin{array}{cccc} & T_1 & T_2 & T_3 & T_4 \\ Antenna\ 1 & \begin{bmatrix} b_1 & b_2^* & b_3 & b_4^* \\ Antenna\ 2 & b_2 & -b_1^* & -b_4 & b_3^* \\ Antenna\ 3 & b_3 & b_4^* & -b_1 & -b_2^* \\ Antenna\ 4 & b_4 & -b_3^* & b_2 & -b_1^* \end{bmatrix} \end{array}$$

where b_1, b_2, b_3, and b_4 are the symbols, which may be encoded samples, derived from data substreams 1, 2, 3, and 4, respectively, and * indicates complex conjugate. As

20   indicated, the rows of the matrix represent the different antennas, while the columns represent different symbol periods (T_i, $i=1 .. 4$).

This approach may be used in systems that employ direct sequence spreading, e.g., code division multiple access (CDMA) systems. In such systems, each entry of the matrix is modulated, i.e., multiplied, by an orthogonal spreading code sequence

25   represented by one of horizontal vectors $\overline{c}_l$, $l=1 .., L,$ each of which spans 1 symbol period and contains N chips, where N is the spreading gain.

In a receiver, the received signal is first applied to a bank of L correlators, where despreading, in the case of a spread spectrum signal, or otherwise the simpler version thereof, temporal subsampling, is performed, producing L preprocessed sequences. The

30   preprocessed sequences are further processed, either jointly or individually, to ultimately develop a reconstructed version of the source bit stream.

Advantageously, using this methodology, the samples of the data substreams may be encoded, as indicated, prior to being incorporated into the matrix using conventional coding techniques, e.g., turbo coding, and the advantages of such coding may be exploited at the receiver. Further advantageously, the coding of each of the data substreams is independent of, i.e., decoupled from, the coding of any of the other data substreams.

Brief Description of the Drawing

In the drawing:

FIG. 1 shows an exemplary transmitter arranged in accordance with the principles of the invention; and

FIG. 2 shows an exemplary embodiment of a receiver arranged in accordance with the principles of the invention.

Detailed Description

The following merely illustrates the principles of the invention. It will thus be appreciated that those skilled in the art will be able to devise various arrangements which, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and scope. Furthermore, all examples and conditional language recited herein are principally intended expressly to be only for pedagogical purposes to aid the reader in understanding the principles of the invention and the concepts contributed by the inventor(s) to furthering the art, and are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents as well as equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure.

Thus, for example, it will be appreciated by those skilled in the art that any block diagrams herein represent conceptual views of illustrative circuitry embodying the principles of the invention. Similarly, it will be appreciated that any flow charts, flow diagrams, state transition diagrams, pseudocode, and the like represent various processes which may be substantially represented in computer readable medium and so executed by a computer or processor, whether or not such computer or processor is explicitly shown.

The functions of the various elements shown in the FIGs., including functional blocks labeled as "processors", may be provided through the use of dedicated hardware as

well as hardware capable of executing software in association with appropriate software. When provided by a processor, the functions may be provided by a single dedicated processor, by a single shared processor, or by a plurality of individual processors, some of which may be shared. Moreover, explicit use of the term "processor" or "controller"

5   should not be construed to refer exclusively to hardware capable of executing software, and may implicitly include, without limitation, digital signal processor (DSP) hardware, read-only memory (ROM) for storing software, random access memory (RAM), and non-volatile storage. Other hardware, conventional and/or custom, may also be included. Similarly, any switches shown in the FIGS. are conceptual only. Their function may be

10   carried out through the operation of program logic, through dedicated logic, through the interaction of program control and dedicated logic, or even manually, the particular technique being selectable by the implementor as more specifically understood from the context.

In the claims hereof any element expressed as a means for performing a specified

15   function is intended to encompass any way of performing that function including, for example, a) a combination of circuit elements which performs that function or b) software in any form, including, therefore, firmware, microcode or the like, combined with appropriate circuitry for executing that software to perform the function. The invention as defined by such claims resides in the fact that the functionalities provided by the

20   various recited means are combined and brought together in the manner which the claims call for. Applicant thus regards any means which can provide those functionalities as equivalent as those shown herein.

Unless otherwise explicitly specified herein, the drawings are not drawn to scale.

FIG. 1 shows an exemplary transmitter arranged in accordance with the principles

25   of the invention. The transmitter of FIG. 1 uses a decoupled space-time coding approach for each of a number, L, of data substreams that are derived from a source bit stream. The L data substreams are processed so that they may be transmitted via four transmit antennas. Advantageously, each data substream employ conventional channel coding.

FIG. 1 shows a) demultiplexer (DEMUX) 101; b) encoders 103, including

30   encoders 103-1 through 103-L; c) space time multiplexer 105; d) radio frequency (RF) units 107, including RF units 107-1 through 107-4; and e) antennas 109, including antennas 109-1 through 109-4.

Demultiplexer 101 divides the source bit stream it receives as an input into L data substreams. Each of the L data substreams supplied as an output by demultiplexer 101 is

35   optionally encoded by a respective one of optional encoders 103 to produce encoded data substreams. Advantageously, encoders 103 may employ conventional channel coding,

such as turbo coding. Encoders 103 may also perform digital modulation, e.g., mapping the samples to a discrete alphabet prior to doing the actual encoding. The encoded data substreams are supplied to space time multiplexer 105.

Each sample supplied as an output by one of encoders 103, or by demultiplexer 101 in the event encoders 103 are omitted, is referred to herein as a symbol. The time duration of a symbol is referred to as a symbol period.

Every symbol period, space time multiplexer 105, processes the symbols of each of the encoded data substreams supplied by encoders 103 so as to form four transmit time sequences, each time sequence spanning at least L symbol periods. Each of the symbols is processed to develop its complex conjugate. In one embodiment of the invention, where $L=4$, the four symbols, their complex conjugates, the negative of the symbols and the negative of the complex conjugates are arranged by space time multiplexer 105 to form a matrix $\mathbf{B}$. Each row of matrix $\mathbf{B}$ corresponds to one of antennas 109. More specifically, the elements of each row represent the samples of a temporal sequence that is emitted by the corresponding one of antennas 109 in L symbol periods, unless direct sequence spreading is used, as described further hereinbelow.

In such an embodiment of the invention, the matrix $\mathbf{B}$ is arranged as follows:

$$
\begin{array}{c}
\begin{array}{cccc} T1 & T2 & T3 & T4 \end{array} \\
\begin{array}{c} Antenna\ 1 \\ Antenna\ 2 \\ Antenna\ 3 \\ Antenna\ 4 \end{array}
\begin{bmatrix}
b_1 & b_2^* & b_3 & b_4^* \\
b_2 & -b_1^* & -b_4 & b_3^* \\
b_3 & b_4^* & -b_1 & -b_2^* \\
b_4 & -b_3^* & b_2 & -b_1^*
\end{bmatrix}
\end{array}
$$

where b_1, b_2, b_3, and b_4 are the symbols from the encoded data substreams supplied as outputs from encoders 103-1, 103-2, 103-3, and 103-4, respectively, and * indicates complex conjugate. As indicated, the rows of matrix $\mathbf{B}$ represent the different antennas, while the columns represent different symbol periods (Ti, i=1 .. 4).

In the event that the inventive technique is employed in a system that employs direct sequence spreading, e.g., code division multiple access (CDMA) system, space time multiplexer 105 further multiplies each element of the lth column, $l=1 \ldots L$, of an unspread matrix $\mathbf{B}$ by a spreading code sequence represented by $\overline{c}_l$, which spans 1 symbol period and contains N chips, where N is the spreading gain. The set $\overline{c}_l$, $l=1 \ldots L$, may be orthogonal. Thus, the spread matrix $\mathbf{B}$, which is transmitted, becomes

$$\begin{bmatrix} b_1\overline{c}_1 & b_2^*\overline{c}_2 & b_3\overline{c}_3 & b_4^*\overline{c}_4 \\ b_2\overline{c}_1 & -b_1^*\overline{c}_2 & -b_4\overline{c}_3 & b_3^*\overline{c}_4 \\ b_3\overline{c}_1 & b_4^*\overline{c}_2 & -b_1\overline{c}_3 & -b_2^*\overline{c}_4 \\ b_4\overline{c}_1 & -b_3^*\overline{c}_2 & b_2\overline{c}_3 & -b_1^*\overline{c}_4 \end{bmatrix}$$

Each of the time sequences developed by space time multiplexer 105 are supplied as an input to a respective one of radio frequency (RF) units 107, each of which performs all the necessary processing to convert its respective input from baseband to a radio frequency modulated signal. Each of the radio frequency modulated signal developed by each of RF units 107 is supplied to a respective one of antennas 109 from which it is transmitted.

Note that although antennas are shown in FIG. 1, any form of transmit element may be employed, e.g., a light source. Further note that although radio frequency units are shown in FIG. 1, in other embodiments of the invention, e.g., those using light for communicating the transmitted signal, different modulators may be employed

FIG. 2 shows an exemplary embodiment of a receiver arranged in accordance with the principles of the invention. FIG. 2 shows a) antenna 201; b) radio frequency (RF) units 203; c) demultiplexer 202; d) correlator 205-1 through 205-L; e) selective conjugator 206, f) matrix multiplier 207; g) baseband signal processing unit 209; h) optional decoders 211, including decoders 211-1 through 211-L; and i) multiplexer 213.

Antenna 201 receives the signals transmitted by all of antennas 109 (FIG. 1) and supplies an electrical version thereof to RF unit 203 (FIG. 2). RF unit 203 converts the radio frequency signal supplied to it by antenna 201 to a baseband version thereof.

Demultiplexer (demux) 202 performs subsampling, i.e., it divides the received baseband signal into L portions in time, and supplies one portion to each respective one of L outputs to form data substreams which are supplied to optional correlators 205 or directly to respective inputs of selective conjugator 206.

In the event that the inventive technique is employed in a system that employs direct sequence spreading, e.g., a code division multiple access (CDMA) system, each of optional correlators 205 is supplied with a respective one of an orthogonal spreading code sequence represented as a horizontal vector $\overline{c}_l$, $l=1$ .., L where each of orthogonal spreading code sequences $\overline{c}_l$, spans 1 symbol period and contains N chips, where N is the spreading gain. Thus, correlators 205 perform despreading which is the inverse of the spreading performed in space time multiplexer 105, and each supplies as an output a despread data substream which is supplied to selective conjugator 206.

Selective conjugator 206 determines the complex conjugate of any of the outputs d_i' of demultiplexer 202 or optional correlators 205 that is required to ensure that the system is not over parametrized. In other words, there should only be one form of each symbol that is being sought in the system of linear equations that describes the input to

5   matrix multiplier 207. This system of linear equations is generally represented, when the channel is a flat-faded channel and in the absence of noise, as $\mathbf{d}=\mathbf{Hb}$, where $\mathbf{d}$ is the vertical vector that is the output of selective conjugator 206, $\mathbf{H}$ is a matrix of derivatives of channel coefficients h_1, h_2, h_3, and h_4, $\mathbf{b}$ is a vertical vector formed from $b_1 \ldots b_L$., i.e., if symbol b_1 appears in $\mathbf{b}$, then b_i^* should not appear. This is necessary in order that the

10   inputs to matrix multiplier 207 be a linear function of only the symbols b_i, i=1 .. L.

For example, if L=4 and matrix $\mathbf{B}$ is arranged in the manner described hereinabove, i.e.,

$$\begin{bmatrix} b_1 & b_2^* & b_3 & b_4^* \\ b_2 & -b_1^* & -b_4 & b_3^* \\ b_3 & b_4^* & -b_1 & -b_2^* \\ b_4 & -b_3^* & b_2 & -b_1^* \end{bmatrix}$$

15   then $\mathbf{d}=\begin{bmatrix} d_1' \\ d_2'^* \\ d_3' \\ d_4'^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 & h_3 & h_4 \\ -h_2^* & h_1^* & -h_4^* & h_3^* \\ -h_3 & h_4 & h_1 & -h_2 \\ -h_4^* & -h_3^* & h_2^* & h_1^* \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix}$

so it is necessary to complex conjugate d_2' and d_4' to develop $\mathbf{d}=\mathbf{Hb}$.

Matrix multiplier 207 operates on the received vertical vector $\mathbf{d}$ to produce L match filtered outputs. To this end, matrix multiplier 207 also receives, or derives, an L by L matrix $\mathbf{H}^\dagger$, where $\dagger$ denotes complex conjugate transpose, also known as Hermitian

20   transpose. In an embodiment of the invention where L is 4. $\mathbf{H}$, as noted above, is the following matrix

$$\begin{bmatrix} h_1 & h_2 & h_3 & h_4 \\ -h_2^* & h_1^* & -h_4^* & h_3^* \\ -h_3 & h_4 & h_1 & -h_2 \\ -h_4^* & -h_3^* & h_2^* & h_1^* \end{bmatrix}$$

25   where h_i is the complex channel coefficient from the ith transmit antenna to the receiver antenna assuming all the channels are flat faded channels. The matrix $\mathbf{H}^\dagger$,

multiplies from the left the L by 1 vertical vector $\mathbf{d}$ formed by the outputs of correlators 205 to produce a new L by 1 vertical vector $\mathbf{f}$ whose L entries are the inputs to baseband signal processing unit 209, i.e., $\mathbf{f} = \mathbf{H}^\dagger \mathbf{d}$.

The L match filtered outputs are supplied to baseband signal processing unit 209

5   in order to extract therefrom L data substreams. In various embodiments of the invention, in baseband signal processing unit 209 a specified matrix $\mathbf{W}$ multiplies from the left vertical vector $\mathbf{f}$ to produce a new L by 1 vertical vector $\mathbf{r}$, so that $\mathbf{r} = \mathbf{Wf}$. In one embodiment of the invention, a decorrelating process, also known as zero forcing, is employed in which the matrix $\mathbf{W} = \mathbf{K}^{-1}$ is computed, where $\mathbf{K} = \mathbf{H}^\dagger \mathbf{H}$. In one embodiment

10 of the invention, $\mathbf{W} = \mathbf{K}^\dagger (\mathbf{K}\,\mathbf{K}^\dagger + \lambda\,\mathbf{K})^{-1}$, where λ is a real scalar. More particularly, λ may be equal to σ_n^2 / σ_b^2 where σ_n^2 is the channel noise variance and σ_b^2 is the variance of any of b_i, where $i = 1 .. L$. Such a receiver is known as a minimum mean squared error (MMSE) receiver.

In accordance with an aspect of the invention, in performing the multiplication in

15 baseband signal processing unit 209 when $L=4$ for the foregoing embodiments, it is possible to speed up the calculations with no loss in accuracy by subdividing the matrix multiplication process into two portions, the first portion using the first and third element of vertical vector $\mathbf{f}$ and the second portion using the fourth and second element of vertical vector $\mathbf{f}$, specifically in that order. A particular 2 x 2 matrix that is employed for the

20 multiplication from the left for both portions is derived as follows. First derive 2 x 2 matrix $\mathbf{K}'$ which corresponds to deleting the second and fourth rows and columns of 4 x 4 matrix $\mathbf{K}$. Then, determine 2 x 2 matrix $\mathbf{W}'$ using the same process by which $\mathbf{W}$ is derived from $\mathbf{K}$, but employing $\mathbf{K}'$ in lieu of $\mathbf{K}$ for the respective processing desired, e.g., zero forcing or MMSE.

25 In other embodiments of the invention, baseband signal processing unit 209 may employ non-linear processing techniques, such as non-linear multi-user detection, including maximum likelihood multi-user detection and interference cancellation. Such non-linear processing techniques may also employ the partitioning technique described above to reduce computational complexity without sacrificing accuracy.

30 Each of the L data substreams is then, optionally, decoded by a respective one of optional decoders 211 to which it is supplied. The decoding performed by decoders 111 advantageously is the inverse of that performed by encoders 103, and as such they may also perform digital demodulation.

Note that in other embodiments of the invention the decoding process may be

35 combined with the processing of baseband signal processing unit 209. In such

embodiments of the invention, it is possible to perform joint decoding, i.e., decoding using information from more than one data stream. Such embodiments of the invention may be especially suitable for the use of non-linear processing techniques in baseband signal processing unit 209. Furthermore, note that decoding may be eliminated entirely if

5 no encoders 103 (FIG. 1) were included in the transmitter.

The decoded L data substreams are then supplied as an input to multiplexer (MUX) 213 (FIG. 2) which interleaves them in the inverse pattern of DEMUX 101 to reconstruct the source bit stream.

In other embodiments of the invention, the functionality of matrix multiplier 207

10 may be absorbed into the processing performed by baseband signal processing unit 209. In yet further embodiments of the invention, the functionality of matrix multiplier 207 may be eliminated.

Note that the decision functionality which is that part of the process which selects the closest constellation point may be performed in either baseband signal processing unit

15 209, in decoders 211, or distributed across both at the discretion of the implementor based on the particular decoding selected. Furthermore, the particular algorithm employed to achieve the decision functionality is at discretion of the implementor.

Advantageously, using this methodology, the samples of the data substreams may be encoded, as indicated, prior to being incorporated into the matrix using conventional

20 coding techniques, e.g., turbo coding, and the advantages of such coding may be exploited at the receiver. Further advantageously, the coding of each of the data substreams is independent of, i.e., decoupled from, the coding of any of the other data substreams.

In another embodiment of the invention, where $L=4$, the matrix $\mathbf{B}$ is arranged as

25 follows:

$$\begin{bmatrix} b_1 & b_2^* & b_3 & b_4^* \\ -b_2 & b_1^* & b_4 & -b_3^* \\ b_3 & b_4^* & -b_1 & -b_2^* \\ -b_4 & b_3^* & -b_2 & b_1^* \end{bmatrix}$$

where b_1, b_2, b_3, and b_4 are the symbols from the encoded data substreams supplied as outputs from encoders 103-1(FIG. 1), 103-2, 103-3, and 103-4, respectively, and * indicates complex conjugate. Similarly, in another embodiment of the invention,

30 the transpose of the immediately preceding matrix B, i.e.,

$$\begin{bmatrix} b_1 & -b_2 & b_3 & -b_4 \\ b_2^* & b_1^* & b_4^* & b_3^* \\ b_3 & b_4 & -b_1 & -b_2 \\ b_4^* & -b_3^* & -b_2^* & b_1^* \end{bmatrix}$$

may be employed.

In another embodiment of the invention, where $L=4$, the matrix **B** is arranged as follows:

$$\begin{bmatrix} b_1 & b_2 & b_3 & b_4 \\ b_2^* & -b_1^* & b_4^* & -b_3^* \\ b_3 & -b_4 & -b_1 & b_2 \\ b_4^* & b_3^* & -b_2^* & -b_1^* \end{bmatrix}$$

where b_1, b_2, b_3, and b_4 are the symbols from the encoded data substreams supplied as outputs from encoders 103-1(FIG. 1), 103-2, 103-3, and 103-4, respectively, and * indicates complex conjugate.

It will be readily recognized by those of ordinary skill in the art that in lieu of starting the process with the set of b_1, b_2, b_3, and b_4, any other set of derivatives of b_1, b_2, b_3, and b_4 may be employed by the implementor, with corresponding changes made throughout the process. Furthermore, the ordering of the derivatives of the substreams is also solely at the discretion of the implementor, again with corresponding changes made throughout the process. Thus, for example, one may select to use the set b_4, b_1^*, $-b_2$, b_3.

Those of ordinary skill in the art of non-flat faded channels will be able to apply the techniques of the invention for use with non-flat faded channels.

In another embodiment of the invention, multiple receive elements are employed. The symbols are reconstructed for each of the data substreams developed at each receive element in the manner described hereinabove. They may then be combined to develop an improved estimate of the original symbol. Such combination may be achieved, for example, by averaging values for each corresponding symbol.